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ABSTRACT

This publication is one of a series of information booklets for the general public published by the United States Atomic Energy Commission. This booklet deals with the handling, processing and disposal of radioactive wastes. Among the topics discussed are: The Nature of Radioactive Wastes; Waste Management; and Research and Development. There are four appendices which list: Naturally Occurring Radioisotopes Encountered in Mining, Milling, and Fuel Preparation in the Uranium Fuel Cycle; Principle Fission-product Radioisotopes in Radioactive Wastes; Principle Activation-product Radioisotopes Produced by Neutron Irradiation of Nonfuel Materials; and a List of Firms Licensed to Receive and Dispose of Radioactive Wastes. A list of suggested references at the popular and technical level, including books, reports, articles, and motion pictures, is included. Schools and public libraries may obtain a complete set of the booklets without charge. (BT)

Radioactive Wastes

by Charles H. Fox

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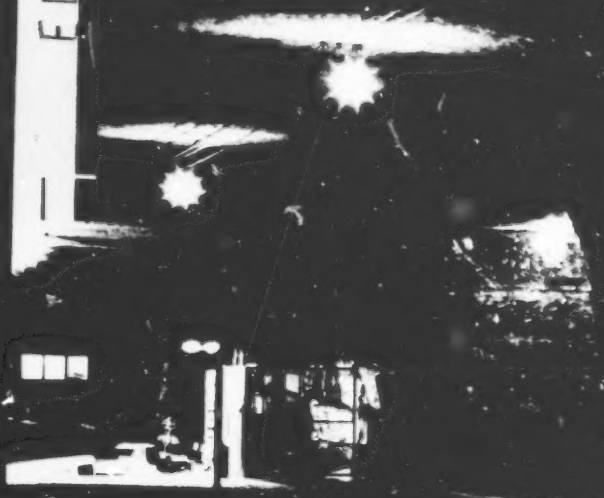

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Nuclear energy is playing a vital role in the life of every man, woman, and child in the United States today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them.

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THE COVER

The main corridor of the Carey Salt Company Mine in Lyons, Kansas, 1000 feet below the surface of the earth. The ceiling height in the corridor is 14 feet. The Oak Ridge National Laboratory has carried out a radioactive waste disposal experiment in this mine to determine heat and radiation effects on salt from high-level solidified wastes and to demonstrate radioactive waste handling techniques in this environment. Results of these tests show that this may provide safe and efficient storage for high-level radioactive wastes. (See page 33 and Figure 16 for more information on this research.)

THE AUTHOR

CHARLES H. FOX is a consultant in nuclear engineering with many years' experience in industry, much of it with The Martin Company, where he was Chief, Advance Design, and later program manager for the PM-3A nuclear power plant, now operating in the Antarctic. Mr. Fox won the Eshbach Award as the outstanding graduate of the Technological Institute, Northwestern University, where he obtained his degree in chemical engineering. He served as an instructor in nuclear engineering at Martin and for several years was a member of the Advisory Committee on Nuclear Education at the Drexel Institute of Technology. He has frequently addressed high school groups and civic clubs on nuclear energy.

Radioactive Wastes

By CHARLES H. FOX

MEN AND ASHES

An archaeologist kneels in the Mexican valley of Tehuacan, gently brushing the dirt from crude artifacts discarded thousands of years before. Fragments of earthenware and chipped stones in the ashes of ancient fires tell their story. They are wastes from the first human culture on the North American Continent.

Today, in the wheat fields of Kansas, tons of straw left behind by threshing machines must be disposed of each year by baling for later use or by burning. Wastes of straw may never be seen by archaeologists of the future, but other wastes of our time will intrigue them — piles of slag from steel mills, city dumps under tons of soil, and mountains of rusted automobiles.

Almost every act of man leads to wastes of one sort or another — hunters' ejected cartridges, smoke from powerplant chimneys, wastepaper in schoolrooms, or the curls of childhood lost forever on the barbershop floor.

The nuclear industry is no exception. Managers of nuclear installations are concerned with the handling, processing, and disposal of wastes. In many ways this activity is comparable to other disposal processes, but it is different in a few important respects.

The most significant difference between nuclear wastes and those of other industries is that nuclear wastes are radioactive, and this accounts for the special methods required for their disposal. The highly radioactive wastes from spent nuclear fuels, in particular, pose a challenging problem. They cannot be piled in open fields or dumped into rivers or the ocean. Another problem exists because of the millions of gallons of water containing traces of radioactivity that must be disposed of each year. The management of radioactive wastes is, indeed, a complex and interesting activity.

Since 1942, when the first self-sustaining chain reaction was achieved, the nuclear industry has grown vigorously. Over 300 operating reactors are now in use.* In addition, radioactive materials are increasingly regarded as important tools for research, medicine, and industry. As the

Figure 1 *The Dresden Nuclear Power Station near Chicago, Illinois, is an example of America's growing nuclear industry.*

*For more about nuclear reactors, see *Nuclear Reactors* and *Research Reactors*, companion booklets in this series.

nuclear era continues, there will obviously be more radioactive waste. Clearly the methods used for the control and disposal of wastes must not only be appropriate to a widespread, lusty endeavor but also be safe and economical.

In the U. S. nuclear program, the Atomic Energy Commission (AEC) has the function of protecting the public against the hazards of radioactive materials. Regulations have been developed through research to ensure effective control without unduly restricting the growth of nuclear industry. The AEC also directs research to develop new methods of radioactive waste management. Much remains to be done, but the work already promises that disposal of radioactive wastes will not erect economic barriers to our nuclear future.

THE NATURE OF RADIOACTIVE WASTES

Many kinds of radioactive wastes are produced by the nuclear industry.* AEC licensing procedures and regulations deal with more than 900 radioisotopes† of 100 elements. Wastes containing these isotopes may be in the form of gases, liquids, or solids, may be soluble or insoluble, and may give off various types of radiation at many energy levels. Although many radioisotopes decay rapidly, some require hundreds of years to decay to safe levels.

The hazards of radioactive materials stem from their basic characteristics. Radiation cannot be detected by the senses (except in massive doses); its effects are often cumulative and may not be evident for some time; and it can damage both an individual and, by impairing his reproductive cells, future generations of his descendants. Fortunately the nature of radioactivity also makes it possible to detect its presence with certainty and remarkable accuracy.

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*For a discussion of the nature, measurement, and control of radioactivity at nuclear power plants, see *Atomic Power Safety*, another booklet in this series.

†Radioisotopes are radioactive forms of elements. For definitions of unfamiliar words, see *Nuclear Terms, A Brief Glossary*, a companion booklet in this series.

One final point — radioisotopes are immune to outside influence. Each isotope decays at its own particular rate regardless of temperature, pressure, or chemical environment and continues to do so no matter what is done to it. Allowing radioisotopes to decay naturally is the only practical means of eliminating their radioactivity. All processing, storing, and use of radioisotopes must therefore be considered as an intermediate step leading finally to disposal by decay.

Sources of Radioactive Waste

Radioactive wastes are created wherever radioactive materials are used. By far the greatest source of wastes is the nuclear fuel cycle: The mining, milling, and preparation of fuel for reactors and weapons produce wastes containing natural radioisotopes; and fuel irradiation and subsequent processing produce wastes rich in fission products. Additional wastes are produced by irradiation of nonfuel materials in and around reactors. Let us consider these sources.

NATURAL RADIOACTIVITY refers to the radioactivity of materials found in nature. These materials are present in uranium and thorium ores, nature's nuclear fuels. Wastes from mining, ore milling, and fuel fabrication therefore contain this natural radioactivity, which consists primarily of the natural radioisotopes of uranium, thorium, radon (a gas), and radium (see Figure 2, page 6, and Appendix I).

Most mines are in dry formations, but some must be kept dry by pumping out hundreds of gallons of water per minute. This water contains only traces of radioisotopes and poses no significant health hazard. In uranium ore-concentrating mills, liquid wastes are discharged to ponds or lagoons at a rate of 300 to 500 gallons per minute (for an average mill processing 1000 tons of ore per day). There are over 20 such mills in the United States. Radium is the principal radioisotope in mill wastes and is incorporated in the solid residues, called "tailings", in an insoluble form.

In "feed" preparation, the next step in the fuel cycle, ore concentrates are taken from the mills and chemically

purified. This produces uranium salts, or feed, for the gaseous-diffusion plants (for separation of uranium-235 from other isotopes of uranium); or it converts concentrates to metallic uranium or uranium oxide for fuel elements. For each ton of uranium processed, approximately 1000 gallons of liquid wastes are produced.

The purified uranium used in the fabrication of fuel elements has extremely low activity because the radium, thorium, and several radioactive decay products have been removed in earlier steps of the cycle. Liquid wastes from fuel fabrication plants are of small volume and very low radioactivity. Contaminated scrap is also produced at fabricating plants.

FISSION PRODUCTS produced during the irradiation of nuclear fuels in reactors are by far the largest source of radioactive waste in terms of contained radioactivity. When each uranium atom fissions, it breaks into two major fragments appropriately called fission products. Fission products are radioactive; they undergo one or more steps of radioactive decay before reaching a stable, harmless condition (see Appendix II). Valuable fuel material remains in the irradiated fuel along with the accumulated fission products; so recovery of this fuel is important. Chemical processing of irradiated nuclear fuels is, therefore, an inescapable part of the nuclear industry. The processing creates highly radioactive wastes consisting not only of fission products but also of some activated reactor materials, chemicals, and corrosion products.*

Chemical processing of irradiated fuel is presently done at AEC plants, but private industry will enter this field as the nuclear industry grows. Already the first commercial plant is under construction in the state of New York by Nuclear Fuel Services, Inc. (see Appendix IV).

A number of solvent-extraction processes are used to separate remaining fuel from waste products in used fuel elements. From 1 to 100 gallons of highly radioactive liquid result from each kilogram of uranium processed — 1 to

*For more about fuels and fuel processing, see *Atomic Fuel*, another booklet in this series.

Type of waste radioactivity	Source of waste	Form of waste
Natural activity	Mining of uranium ores	Solids
		Liquids
		Gases and dusts
	Fuel fabrication plants	Solids
		Liquids (acid)
		Dusts
Fission-product activity	Fuel irradiation and processing	Solids (from purposeful solidification)
		Liquids (with strontium and cesium removed)
		Gases
Activation-product activity	Reactor materials unavoidably irradiated during operation	Solids
		Liquids (dissolved material)
		Gases
	Purposeful irradiation to produce useful isotopes	Solids

Figure 2 *Typical radioactive wastes and disposal methods. See ap-*

10 gallons in processing natural or slightly enriched* uranium and 10 to 100 gallons in the case of highly enriched uranium. Up to now, most of the fuels processed have been natural-uranium fuels from the AEC's plutonium-production

*Enriched uranium is uranium in which the proportion of uranium-235 has been increased by putting the natural element through an isotope-separation process, such as gaseous diffusion. See Appendix I for natural-uranium content of uranium-235.

Typical isotopes	Type of radiation	Disposal methods
Uranium-238	α, γ	Pile in open
Thorium-230	α, γ	Seep into ground
Radon-222	α	Ventilate mine
Uranium-238 Uranium-235	α, γ	Decontaminate
Uranium-238 Uranium-235	α, γ	Neutralize, concentrate, and bury residue
Uranium-238 Uranium-235	α, γ	Ventilate, filter, and disperse to air
Strontium-90 Cesium-137	β β, γ	Encase in container and store permanently (~600 years)
Technetium-99 Ruthenium-103 Cerium-144	β, β, γ β, γ	Store in tanks for several years; then solidify in place
Iodine-131	β, γ	React with chemicals to bind in solid, e.g., silver iodide
Krypton-85	β, γ	Disperse to air
Aluminum-28 Manganese-56	β, γ β, γ	Package and ship for land burial
Cobalt-58	β^+, γ	Evaporation or ion-exchange; bury residue
Nitrogen-16	β, γ	Hold for decay (very short life); then disperse to air
Cobalt-60	β, γ	Ship for burial when no longer useful (long life)
Phosphorus-32	β	Store for decay to safe levels (short life)

pendices for more detail and explanation.

reactors, but increasing amounts of fuel from nuclear-powered electric plants will have to be processed in the future.

Predictions vary on the amount of high-level waste that will be produced by chemical processing of fuels from nuclear power plants. Current estimates are that some 100,000 gallons will be produced in 1970 and that the amount will increase to about 6 million gallons per year by the

Figure 3 *Open-pit mine in New Mexico is a source of uranium ore that initiates the nuclear fuel cycle.*

end of the century. Large quantities of less radioactive wastes also will be produced; some 4 billion gallons have been produced and disposed of over the past 20 years. Large as these quantities are, they are small in comparison to the volumes of waste processed in other industries, such as paper mills, chemical plants, and sewage-disposal plants.

ACTIVATION PRODUCTS are produced during the irradiation of nonfuel materials located near the fuel in nuclear reactors. Structural materials are activated (made radioactive) by the absorption of neutrons, as are impurities in the coolant* and often the coolant itself. Traces of iron, nickel, and other corrosion products, for example, are carried along with the coolant in some types of reactors and irradiated as they pass through the reactor. Appendix III lists typical activation-product radioisotopes.

*Coolant is a term identifying the fluid that flows through a reactor to remove or transfer heat. Water is most commonly used, but air, carbon dioxide, oils, sodium, and potassium also have been used.

Waste management operating experience at six American nuclear power plants — Dresden-I in Illinois, Big Rock Point in Michigan, Humboldt Bay in California, Elk River in Minnesota, Indian Point-I in New York, and Yankee in Massachusetts — has recently been assessed. The waste volumes handled in nuclear plants are not large in comparison with wastes from many other industries and the total radioactivity is quite small. Radioactivity concentrations in power plant effluents have been well below permissible release limits.

The irradiation of reactor coolant produces larger quantities of low-level waste liquid at the AEC's plutonium-production installations, particularly the Hanford Plant in Richland, Washington. Hanford personnel have the problem of disposing of great amounts of water from the Columbia River that is used directly for reactor cooling. At the AEC Savannah River Plant in Aiken, South Carolina, river water is also used, but it does not enter the reactors and does not become irradiated; the reactor coolant is a separate, relatively small quantity of water. Intermediate

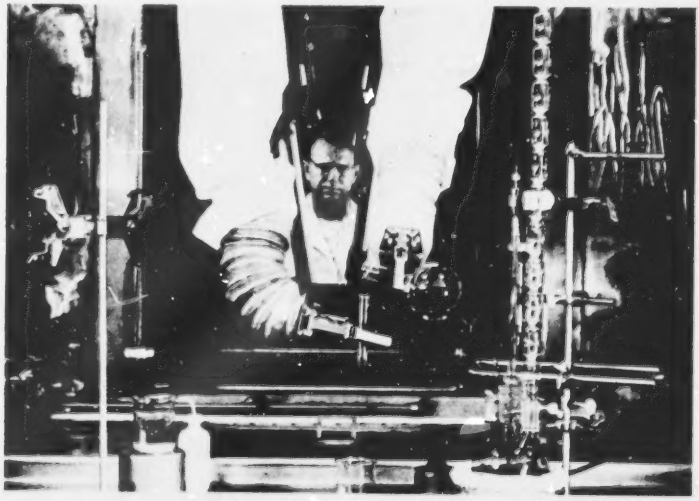

Figure 4 *A "hot cell" worker at the AEC's Oak Ridge National Laboratory in Tennessee uses mechanical hands to separate useful fission products from nuclear wastes.*

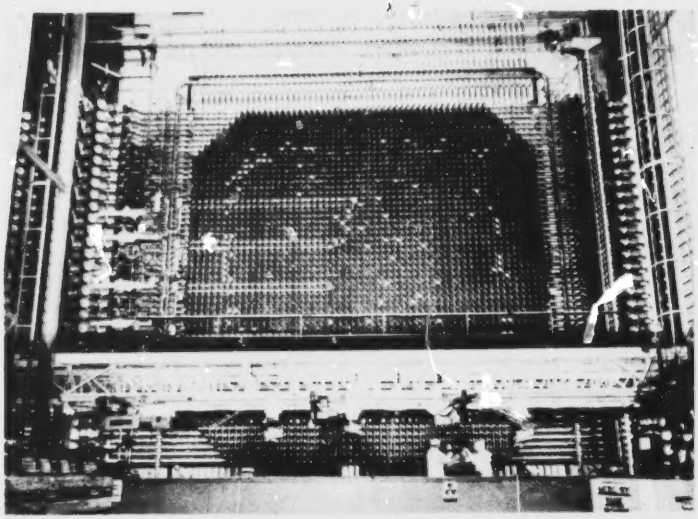

Figure 5 *Face of plutonium-production reactor at the Hanford Plant in Richland, Washington.*

heat exchangers separate the coolant from the river water, and so the problem of quantity disposal does not arise.

Some activation products are gaseous. In water-cooled reactors gaseous products arise from the irradiation of the water as well as from irradiation of any air in the coolant. The gases are mostly short-lived radioisotopes, such as nitrogen-16 or argon-41, but tritium (hydrogen-3) has a half-life* of more than 12 years. Air-cooled reactors produce argon-41, the major examples of this type being the large research reactors operated for many years at Brookhaven and Oak Ridge National Laboratories. Control and disposal of gases is an important aspect of radioactive waste management even though it involves a minor portion of the total radioactivity produced by nuclear industry.

MISCELLANEOUS SOURCES OF RADIOACTIVE WASTES are the more than 4000 establishments making or using nuclear products in the United States. The radioactivity of this

*A half-life is the time required for half a radioisotope to become stable; a period of two half-lives would reduce the quantity of radioactivity to one-quarter the original amount.

great variety of wastes originates in one of the ways we have just discussed—from naturally occurring radioisotopes, fission products, or activation products. These may be in many forms, including chemicals, solids collected in evaporators, resins, and contaminated equipment and materials. Laboratories in hospitals, universities, and private industry produce waste solutions, contaminated gloves and clothing, and broken glassware. Even when sealed radioisotope devices are used, there eventually is need for disposal when the radioactivity has decayed below useful levels.

IN SUMMARY, the four basic sources of radioactive waste materials are:

1. Mining, milling, feed-preparation, and fuel-manufacturing activities, involving naturally occurring radioisotopes. (See Appendix I.)
2. Irradiation and processing of nuclear fuel, involving fission-product radioisotopes. (See Appendix II.)
3. Irradiation of nonfuel materials, involving activation-product radioisotopes, which include several radioisotopes purposely produced for their usefulness. (See Appendix III.)
4. The use of radioisotopes produced in one of the three preceding source categories.

Levels of Radioactivity

Radioactive wastes vary widely in the concentration of radioactive materials. It is convenient to classify them according to their potential hazard, as indicated by their level of activity. Three levels have been defined, somewhat arbitrarily, as follows:

LOW-LEVEL WASTES have a radioactive content sufficiently low to permit discharge to the environment with reasonable dilution or after relatively simple processing. They have no more than about 1000 times the concentrations considered safe for direct release. In liquid form low-level wastes usually contain less than a microcurie* of radioactivity per gallon.

*A microcurie is one millionth of a curie. A curie is a measure of the number of atoms undergoing radioactive disintegration per unit time and is 37 billion disintegrations per second, or about the rate of decay in 1 gram of natural radium.

INTERMEDIATE-LEVEL WASTES have too high a concentration to permit release after simple dilution, yet they are produced in relatively large volumes. Their radioactivity is approximately 100 to 1000 times higher than that of low-level wastes. In liquid form they may contain up to a curie of radioactivity per gallon.

HIGH-LEVEL WASTES contain several hundred to several thousand curies per gallon in liquid form and result from chemical processing of irradiated nuclear fuels. High-level wastes pose the most severe potential health hazard and the most complex technical problems in management.

Potential Effects of Radioactivity

Man has always been exposed to the natural radioactivity in his environment. It is in the soil, in the water we drink, and even in our bodies. This natural "background" level of radioactivity is quite low: The amount of radiation received in one dental X ray is 10 to 100 times that received in a year from natural background activity. A cardinal principle

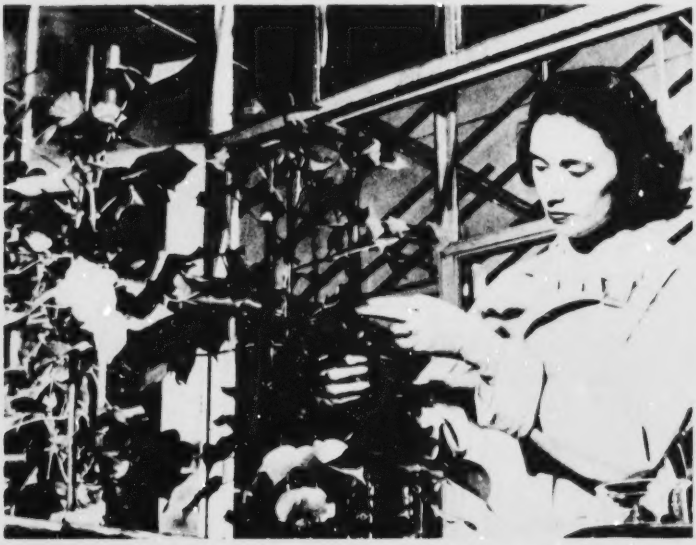

Figure 6 *Research to determine the effects of irradiated soil on cotton plants.*

in waste management has been to preserve this low radiation level in our environment — not to add to it.

Any discharge of radioisotopes to our environment launches a series of interrelated physical and biological events because of the movement of released materials through the atmosphere and underground water and their retention in soil and living organisms. Some of these processes may result in the concentration of radioisotopes that were originally released in very dilute form — thus fish may concentrate phosphorus-32 in their tissues, and oysters may accumulate zinc-65.

The growth of nuclear industry emphasizes the need for complete understanding of natural processes affecting released radioisotopes. Not only the concentration but also the amount of radioactive material is important; care must be taken not to exceed the capacity of the environment. Extensive research is being performed at large atomic energy installations to insure that no unsuspected environmental effects will result from the carefully controlled release of radioactivity.

Equally important is the intensive study of the long-term effects of radiation on man himself. Radiation can affect an exposed individual directly (somatic effects) by damage to body cells, or it can affect his descendants (genetic effects) by damage to reproductive cells. Somatic effects are reduced when a given radiation exposure is spread over a long time. Although there is some evidence that the same principle applies in the case of genetic effects, it is not conclusive.

The isotopes of greatest concern are generally those with the longest half-lives, such as strontium-90 and cesium-137. It is also necessary to consider how each radioisotope is taken into the body and how it behaves, once there. Iodine-131, for example, is passed efficiently through food chains — from the air to grass, thence to cows, and via milk to man, where it is concentrated in the thyroid gland. Radioactive iodine therefore requires stringent control even though its half-life is a relatively short eight days.

The type and energy of emitted radiation and the chemical properties of radioisotopes are other factors that were considered in establishing maximum permissible concen-

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trations for the various radioisotopes. These safe limits are published in the Code of Federal Regulations, which controls management of radioactive waste materials.

WASTE MANAGEMENT

Radioactive waste management consists of the various steps necessary for the safe disposal of radioactive wastes and the control and direction of these measures. Each type of waste requires its own methods for control and disposal. There are, however, two basic principles that are broadly applied:

Concentrate and Contain. Radioactive materials can be stored safely in permanently controlled reservations, but the volume of stored wastes would be prohibitively great if they were not first concentrated. Even high-level wastes can be concentrated or solidified for long-term storage.

Dilute and Disperse. Wastes of appropriately low activity may be reduced to permissible levels for release by dilution in air or in waterways. Wherever materials are to be released to the environment, the amount of radioactivity that can be safely dispersed into that particular environment is determined quantitatively for each specific radioisotope.

In the application of these principles, two considerations are important:

Evaluate Each Case Individually. Each factor affecting waste management must be evaluated for each facility. These factors include accurate data on the specific radioisotopes, their chemical form and concentration, their maximum allowable concentrations for release, and the detailed characteristics of the environment. Suitable treatment and disposal methods then can be chosen and detailed operating standards established.

Check Results. It is important to make certain that operating standards for waste management are met. This requires constant checking on the amount and level of activity handled and released. If conditions change at a site, operating standards must be reexamined and changed if necessary.

Conscientious application of these considerations has been responsible for the success, safety, and economy of

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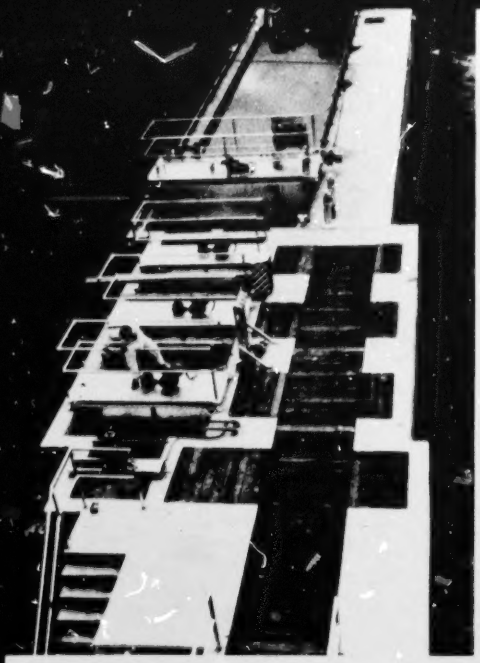

Figure 7 *View of the Process Waste Treatment Plant ponds at Oak Ridge National Laboratory. A workman checks liquid level.*

waste-management activities in this country. There have been no harmful effects to the public or their environment. The cost of waste handling and processing facilities at nuclear power plants averages only 3 to 5% of the total plant cost; the cost of managing high-level wastes from fuel processing is expected to be 1% or less of the total fuel-cycle cost.

Liquid Waste Management: Low and Intermediate Level

Liquid wastes of low and intermediate radioactivity generally have low solids content but vary considerably in chemical and radioisotope content. Treatment and disposal methods differ among nuclear installations, depending both on the waste content and the environment. Let us consider methods in industry and science.

SMALL LABORATORIES, such as educational, industrial, hospital, and medical laboratories, generally produce liquid wastes of low activity. They typically contain only traces of a few isotopes. They are produced in modest quantities and can usually be released by dilution, treated by filtration

or ion exchange,* or retained for shipment to sites equipped for their disposal. Though the amount of waste from these laboratories is small, all agencies licensed for use of radioactive materials must meet disposal standards.

URANIUM MINES AND ORE MILLS produce relatively large quantities of low-level liquid wastes requiring minimal treatment. Where mine pumping is required, as in the Ambrosia Lake area in New Mexico, the radioactivity is so low that the wastes are allowed to seep into nearby desert soil.

The liquid wastes from ore-refining mills are also dispersed into the environment. Solids are settled out in large retention ponds, and the liquid overflows to streams or percolates into the ground. In some locations, mills first remove dissolved radium by chemical treatment. Uranium-mill waste treatment and control have improved substantially in the past five years.

FUEL FABRICATION PLANTS produce modest quantities of low-level acid wastes that are diluted, neutralized, stored to permit decay, and then discharged to waterways. Some industrial fuel manufacturers collect the wastes and ship them elsewhere for disposal. All shipments must conform to Interstate Commerce Commission regulations, and approved containers must be used.

NATIONAL LABORATORIES OF THE AEC produce many kinds of wastes. The methods used to manage them differ in detail but are similar in many respects. In general, liquid wastes from the laboratories range in concentration from less than a hundredth of a microcurie to several hundred microcuries per gallon. Treatment usually includes several of the following steps: filtration, chemical precipitation, ion exchange, evaporation, solidification in concrete, or absorption in porous materials such as vermiculite.

Chemical precipitation is a process of adding chemicals that combine with dissolved radioactive materials to form

*Ion exchange, a process also used in home water softeners, removes dissolved minerals from liquids.

solid particles.* The solids are then separated from the liquid and disposed of by packaging and burial. Chemical precipitation is 60 to 75% effective in removing mixed fission products from low-level laboratory wastes. Ion-exchange resins remove 90 to 99.99% of the contained

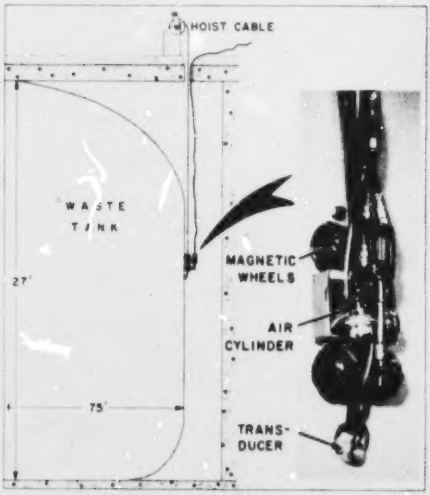

Figure 8 *Engineers at the Savannah River Plant developed this remotely controlled wall thickness tester shown at* left *to detect corrosive thinning of the steel walls of underground tanks containing highly radioactive wastes. An operator at the surface lowers the foot-long "bug" through an access hole on the tank perimeter. Its magnetic wheels grip the steel wall, and the carriage is then rolled up or down to the desired position. A solenoid-actuated air cylinder on the carriage presses a small ultrasonic transducer to the wall; water is jetted over the contact area, providing the necessary coupling. The transducer then emits an ultrasonic pulse that penetrates the wall and is reflected from its inner surface.*

radioactivity. Evaporation of low-level waste retains some 99.99% of the activity in evaporator concentrates.

Waste-management operations at Brookhaven National Laboratory in Upton, New York, illustrate some current methods. Brookhaven is located near the center of Long Island, with farm and residential areas just beyond its boundaries. Several villages are close by. Most of the Brookhaven liquid wastes are generated at the research reactor, the "hot"† laboratory, and the cyclotron building.

*The precipitation process is often demonstrated to chemistry classes by adding a weak silver nitrate solution to a sodium chloride (table salt) solution; a fine white powder, silver chloride, immediately forms and precipitates (settles) to the bottom of the container.

†The term "hot" is applied to radioactive materials or facilities. The term "clean" is often used to indicate an absence of radioactivity.

Low-level wastes are produced in most of the other laboratories. How are these wastes handled?

First, wastes are separated at their source by collection of concentrated wastes in containers. In addition, the reactor and hot laboratory facilities have a separate liquid waste system, and release from this to the general laboratory system is rigorously controlled. The general laboratory system, in turn, is monitored* to ensure control; release from this system to the environment is by way of a filtering system.

Wherever excess activity may accumulate, "hold-up tanks" are provided, and evaporation reduces the stored volume. Some of the concentrate from evaporation is mixed with concrete, solidified, and handled as solid waste. The bulk of the low-level liquid waste, however, is discharged via a separate sewage system to a settling tank that removes most of the solid material. From there the remaining liquid is discharged through a large sand filter, collected in an underlying tile field, chlorinated, and finally discharged to a small stream.

Samples are collected at key points in both the internal system and the nearby environment. These are monitored to assure control. Only several curies of activity are released to the environment annually.

The amount of radioactivity in purified wastes like these has been reduced in recent years. Oak Ridge National Laboratory in Tennessee, for example, in three years reduced the activity released in its low-level wastes to one-tenth the former amount.

NUCLEAR POWER PLANTS that generate electric power process low-level liquid wastes through treatment and storage systems, such as evaporators, ion exchangers, gas filtration, decay holdup tanks, incineration and fixation of solids and liquids in concrete. In many cases, liquid wastes are processed by decay storage without any other treatment. The quantities of radioactivity discharged from nuclear power plants have been well below permissible release limits. Most reactor installations control their wastes

*Monitoring involves measurement of radioactivity with radiation-detection instruments.

Figure 9 *Monitoring residues from liquid wastes. A technician is placing a container of powdered material in a shielded instrument where radiation will be measured by a Geiger counter.*

in accord with the strict standards applying to unidentified mixtures rather than less stringent ones for individual radioisotopes.

No liquid wastes are released into the ground at reactor installations. The waste systems do use decay hold-up tanks, evaporators, ion-exchange systems, filtration, and, in some cases, steam stripping (to remove gases). In a typical water-cooled reactor power plant, there are two sources of liquid waste: the reactor coolant itself and drainage from supporting laboratories and facilities. When necessary, contaminated liquids are processed in evaporators or ion exchangers. The evaporator concentrates and used ion-exchange resins are then retained for later shipment from the site. Ion exchange is typically used for continuous cleansing of reactor coolants, but discharged

reactor water must nonetheless be retained in tanks to allow radioactive decay, or be processed further.

At the Shippingport Atomic Power Station in Pennsylvania, discharged reactor-coolant water is not treated by evaporation or ion exchange but is stored in underground tanks for a month or more, to permit radioisotopes to decay, before being released to the Ohio River.

HANFORD PRODUCTION FACILITIES of the AEC, which produce plutonium, have environmental conditions more favorable than most power-plant and laboratory sites. Hanford is relatively remote from towns and is adjacent to the Columbia River, with its high volume of flow.

The three reactors presently used for plutonium production are cooled by a single pass of river water, which has been treated by coagulation,* settling, and filtration. A fourth reactor is cooled by recirculating water. The water emerging from the single-pass reactors contains activated impurities and corrosion products and must be held in large basins or tanks for 1 to 3 hours; here natural decay reduces the activity by 50 to 70%. The basin water is then released to the Columbia, where it is immediately diluted by the streamflow.

If the basin water acquires unusual radioactivity because of leaks of fission products from fuel elements, it is discharged to trenches and seeps into the ground. This percolation is very effective since the soil retains the radionuclides. The water table at Hanford is 200 to 600 feet below the surface.

Some intermediate-level liquid wastes are also discharged into the ground through trenches or underground cribs at Hanford (see Figure 10). These include wastes from chemical processing of irradiated fuel, condensed vapors from these processes and from waste storage tanks.

Gaseous Waste Management

Gaseous wastes may contain natural radioactivity, fission-product activity, or materials activated by neutron absorption.

*Coagulation and settling are used the world over for water treatment. Added chemicals form a sticky, gelatinous precipitate that removes suspended solids as it settles.

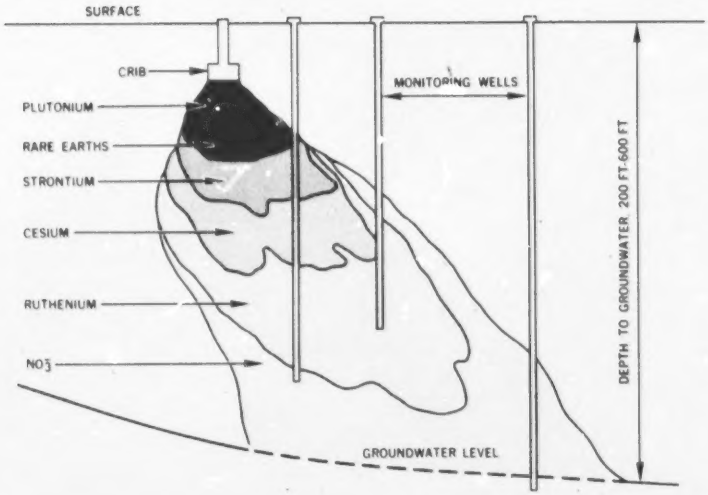

Figure 10 *Disposal of liquid wastes into the ground at the Hanford Plant using an underground crib. The various materials found in these wastes are retained in the soil as shown.*

In the mining, milling, and fabricating of uranium into fuel elements, airborne radioactivity consists of natural radioisotopes in dusts or gaseous radon. These typically occur in low concentrations. Normal ventilation of the work area gives adequate protection. Air discharged from mine ventilation systems usually contains radon-222 and its short-lived decay products; the quantity released to the atmosphere is much less than that naturally given off by rocks of the earth's crust.

The generation of gaseous radioactive wastes at nuclear power plants is different for each type of reactor, but the wastes have been effectively managed in all types of reactors. In general, gaseous wastes are held for an appropriate period of decay and then are released through a high stack after filtration.

Radioiodine is often present in gaseous reactor wastes. Its presence usually determines how the wastes are managed. Activated charcoal can remove up to 99.9% of the radioiodine, but the charcoal's effectiveness soon may be reduced by surface contamination.

Fuel-processing plants control the discharge of radioiodine by a combination of methods. First, the spent (used) fuel is stored from 90 to 120 days to allow natural decay of most of the iodine. Second, most remaining iodine is vaporized during the fuel processing and is removed from other gases by activated charcoal or a chemical-reaction system that converts the iodine into a solid.

Solid Waste Management

Most solid radioactive wastes are of moderately low level and are disposed of by burial. As with liquids and gases, they may contain natural, fission-product, or activation-product radioactivity.

Solid refuse from mining operations contains only a fraction of 1% of uranium oxide. It is usually piled near mine portals; no hazard is involved because of its low radioactivity. Solid refuse from ore-refining mills, called tailings, is of greater concern because it contains most of the radium from the ore. The tailings are usually held in controlled areas to prevent dispersal to the environment. This is more economical than chemical treatment to remove the radium from the large quantities involved. How best to dispose of tailings actually remains an unanswered question for the present.

Solid wastes from feed-material and gaseous-diffusion plants contain only small amounts of natural radioisotopes. They are disposed of by burial in supervised reservations. Some are first treated to remove uranium, especially if it is enriched uranium.

Moderately radioactive solid wastes from laboratories and reactor installations are similar. They consist mostly of residues (used ion-exchange resins or evaporator concentrates) and contaminated equipment and materials (worn-out clothing, filter elements, glassware, blotting paper and other debris). Some establishments burn them to reduce their volume before disposal. Most, however, simply bale and bury them.

LAND BURIAL has been used for about two-thirds of all solid waste produced in the United States through 1963 at five atomic energy reservations—amounting to approximately 30,000 to 50,000 cubic meters per year. Burial sites

are carefully selected, and arrangements must be made to control wastes over a period of many years after they are buried. Only AEC-supervised sites were used until 1963; then the first state-owned burial sites were established for disposal operations by private industry. Burial sites have now been established in Nevada, Kentucky, New York, Illinois, and Washington by private companies.

Burial of solid radioactive waste at AEC burial sites is about 1.5 million cubic feet per year since 1963. This waste volume requires approximately 20 to 25 acres of land annually.

The volumes of low-level solid waste available for commercial burial are estimated at 1 million cubic feet by 1970, 2 million by 1975, and 3 million by 1980.

Land requirements for waste burial have averaged about 1 square foot of ground for 1.5 cubic feet of waste. Solid wastes are now being pressed in standard baling machines before burial, however, to reduce the waste volume 2 to 10 times.

The wastes are generally buried in unlined pits and trenches (see Figure 11). Several feet of earth cover the

Figure 11 *Land burial trench at the Oak Ridge National Laboratory reservation. Each day's accumulation of waste containers is buried by 3 or more feet of earth.*

wastes and hold surface radiation levels so low that exposure for a full year would result in less radiation than results from a typical medical fluoroscopic examination. Higher activity solids are often buried in concrete-lined wells or stored to permit decay of the activity prior to disposal.

High-level Waste Management

High-level wastes from processed nuclear fuels create the most challenging problem in waste management. These wastes produce substantial amounts of heat for a number of years (see Figure 12). Furthermore, their long-lived radioisotopes require hundreds of years to decay to safe

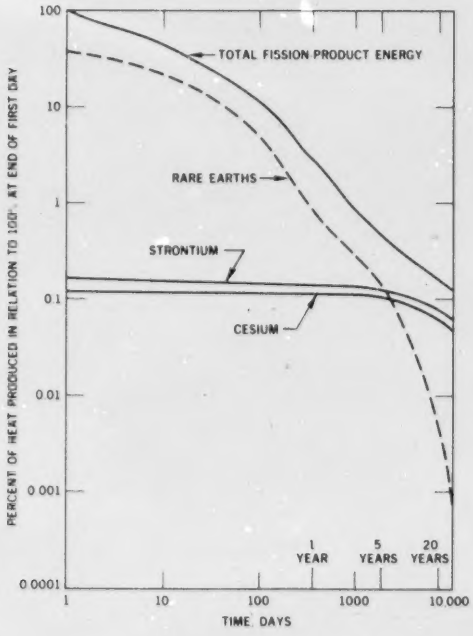

Figure 12 *Heat production in high-level wastes from spent fuel processing. After five years strontium and cesium account for most of the heat production. Note that removal of these isotopes before several years of aging would have little effect on heat production of the remaining mixture.*

levels; during all this time they must be stored away from man and his environment.

TANK STORAGE has been used since high-level waste management first began years ago at the plutonium-production facilities at the Hanford Plant. Since then engineers and scientists of installations at Savannah River, South Carolina, and at the National Reactor Test Site, Idaho, also have used tanks. Almost all such wastes are stored in some 200 underground tanks at the three sites (see Figure 13). The newest type of tank at Savannah River has a steel liner encased in concrete and concrete supporting pillars between tank compartments. The whole tank

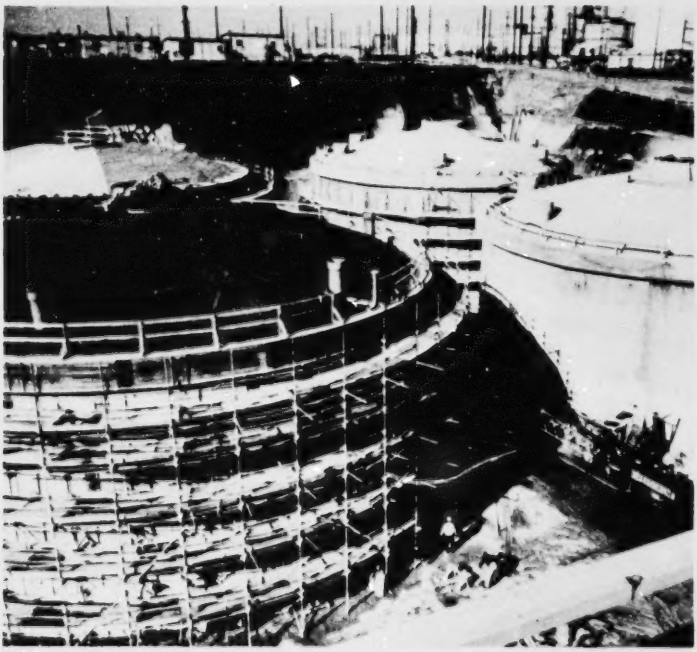

Figure 13 *Large concrete-encased steel tanks under construction at the Savannah River Plant will store high-level wastes. Note forms for prestressing concrete on unfinished tank at left, finished tanks at right, and size of man in center foreground. There are now 80 million gallons of high-activity liquid wastes stored in AEC facilities.*

array sits on a heavy steel "saucer" that extends upward 5 feet at the edges; the saucer, in turn, rests on a concrete slab. Access openings are provided for insertion of instruments, inspection, sampling, and withdrawal of gases.

Tank storage of liquid wastes has proved to be both safe and practical. To extend this for hundreds of years will require periodic replacement of tanks, however, and no valid basis yet exists for accurately predicting tank service life. Experience indicates a reasonable tank-life expectation of several decades, however. Extensive research and development is being carried out to convert highly radioactive liquid wastes to a solid form.

The cost of constructing waste storage tanks has varied from $0.50 to $2.70 per gallon of capacity. The cost depends on size, the acidity of the expected waste, and the need for heat-removal equipment. Most tanks hold from 300,000 to 1,330,000 gallons. The largest ones are for alkaline, low-heating wastes at Savannah River, and they have the lowest unit cost.

The total cost of storage, of course, includes construction of future replacement tanks and annual operating costs; annual expenses range from about ½% to 3% of the original capital cost. It is estimated that the total will be about $100 per gallon for storage over the 600 or more years of storage expected to be needed, assuming a 20-year tank life.

Some installations reduce storage requirements by concentrating wastes, and improved fuel processing has reduced waste volumes from several thousand to several hundred liters per ton of spent fuel.

In spite of these improvements, continuous surveillance of stored liquid wastes is mandatory, as is the need for transfer of the wastes from tank to tank over periods of hundreds of years. These are compelling reasons to search for ways to reduce wastes to solid form.

IN-TANK SOLIDIFICATION plans at the Hanford Plant call for solidification of "nonheating" wastes* by evaporation

*"Nonheating" wastes produce less than 0.2 British thermal units per hour per gallon. (One Btu is the amount of heat energy needed to raise the temperature of 1 pint of water by 1 degree Fahrenheit.)

of the liquid. "Self-heating" wastes, on the other hand, will be separated into two fractions. The first fraction containing the long-lived heat-producing radioisotopes will be absorbed on ion-exchange beds and stored in stainless-steel cylinders; the remainder will become "low-heating" waste after several years and can be solidified in place in the underground tanks. Figure 14 shows the planned in-

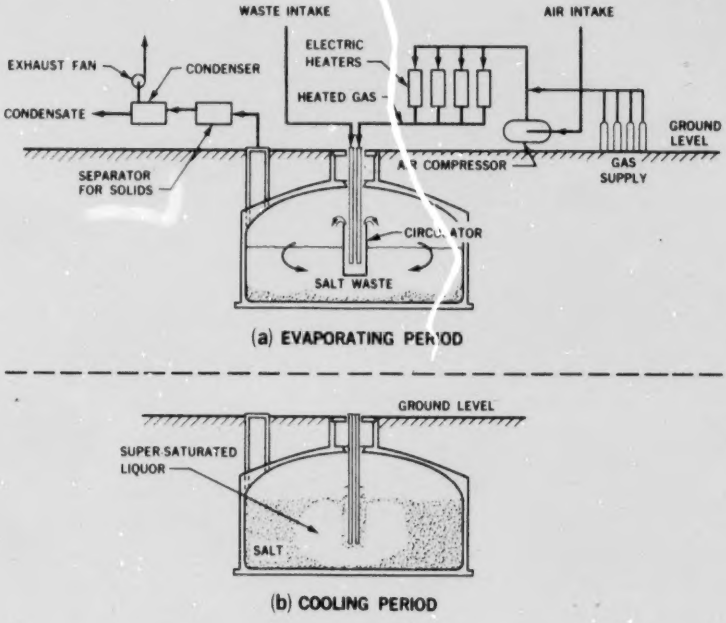

Figure 14 *Proposed in-tank solidification of high-level wastes at the Hanford Plant. More waste can be added as tank level drops during evaporation. (a) Evaporation process; (b) cooling.*

tank solidification process. Heated air (800°C) both heats and circulates the waste, and most of the water is boiled off. Upon cooling, the remaining wastes form a massive salt cake that no conceivable material failure or natural phenomenon could expose to living plants or animals. Other methods of solidifying high-level wastes also are under intensive investigation.

LONG-LIVED FISSION PRODUCTS have been in increasing demand since 1960 for many different uses. At first glance it would seem that separation and use of these radioisotopes might offer a means of waste disposal or result in reduced waste-disposal costs. Although some saving can be realized by combining waste management and fission-product recovery, the ultimate disposal problem will not be appreciably affected, because final disposal is only by the natural decay of radioactive materials. The separation of isotopes must be self-supporting in terms of the value of the separated isotopes.

RESEARCH AND DEVELOPMENT

The nuclear industry is producing increasing amounts of all types of radioactive wastes. Furthermore, it is likely there will be need to locate new plants in less ideal spots than present sites. Environmental restrictions for long-term management of wastes could be quite rigid in some areas. It cannot be expected that methods adequate for an infant industry will be sufficient to cope with the problems of its robust future.

Long-term management of radioactive wastes requires the solution of two principal problems. The first is development of improved methods for processing and disposing of high-level wastes in solid form. The second is improved treatment of large volumes of low-level and intermediate-level wastes to reduce the amount of radioactivity released to the environment.

A number of research activities have begun on these two problems, plus search for more complete understanding of the long-term effects of released radioactivity on man. Although there is still much to be learned, it is worth noting that the hazards and behavior of radioactive materials probably are already better understood than are the hazards of conventional industry and that the safety record of the nuclear industry is without parallel.

We already know that proper management of radioactive wastes can be accomplished without hampering the economic growth of the nuclear industry — in spite of the millions of curies of radioactivity involved, in spite of the hundreds of years of controlled storage required for high-level wastes,

and in spite of the many different reactor types foreseen for future uses.

High-level Waste Processing

The disadvantages of tank storage for hundreds of years have resulted in vigorous search for more practicable methods for the ultimate disposal of high-level wastes. Two general approaches have been dominant. The first seeks to convert aged wastes to solid form. The second seeks to store these solids deep in geologic formations to reduce future handling and the possibility of leaks to man's environment.

CONVERSION-TO-SOLID-FORM METHODS include use of fluidized beds, heated pots, and radiant-heated spray columns to form solid granules. The addition of glass-forming materials to produce stable, glassy, insoluble products is also under study.

Fluidized-bed Calcining. Studies began at Argonne National Laboratory, Argonne, Illinois, in 1955 in the use of fluidized beds for the reduction of liquid wastes to solid form. These studies led to the construction of the Waste Calcining Facility (WCF) at the Idaho Chemical Processing Plant near Idaho Falls, Idaho. This plant processes highly enriched fuels and produces acid wastes requiring storage tanks constructed of stainless steel; thus the storage expense is somewhat higher than that for other facilities.

The WCF was the first full-scale unit in the world for reduction of high-level liquids to solids (see Figure 15). Waste solutions are injected into a 4-foot-diameter vessel called a calciner that contains a heated bed of granular solids, fluidized with air. A fluidized bed is obtained when gas moves up through a bed of solid particles with enough force to raise them and move them about. The heat boils off the liquid and breaks down salts to oxides that deposit in layers on the bed particles. Gaseous products are drawn from the calciner. As solids accumulate, they are drawn off—about half are removed from the lower part of the calciner and half are carried off with the gases, from which they are removed in a series of cyclone separators. In this system air is used to transport the solids.

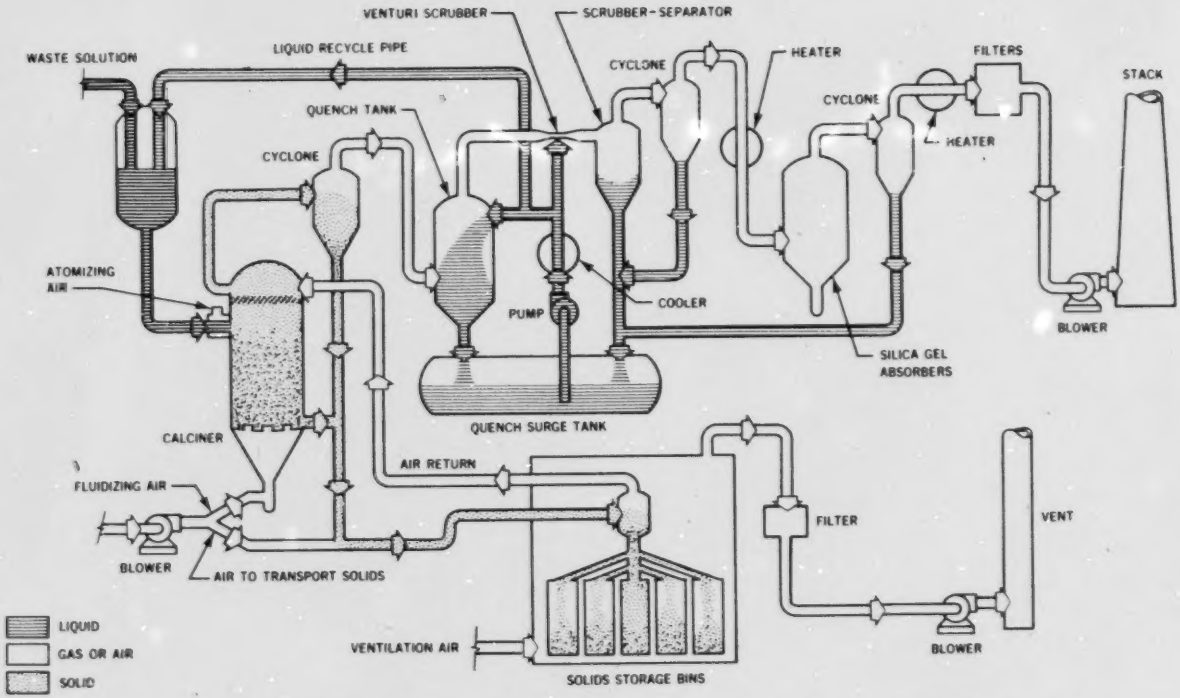

Figure 15 *Flow diagram of the waste calcining facility at the Idaho Chemical Processing Plant.*

The WCF has, during the past $4\frac{1}{2}$ years, processed approximately 1,500,000 gallons of high-level liquid waste to a solid form. It can process 1400 gallons of liquid waste per day.

The bulk volume of the solid particles is about one-tenth that of the liquid wastes from which they are made. The AEC plans to store the solid product underground in vented stainless-steel bins within concrete vaults. Heat from the radioactivity of the product will be removed by air flowing past the outer walls. The solid oxide particles from this process could also be glazed, coated, incorporated into a metal or salt matrix, or converted to glasslike material by addition of appropriate chemicals at high temperature. These methods are being thoroughly investigated.

Waste Solidification Engineering Prototype. There are 3 promising solidification processes to be demonstrated in the Waste Solidification Engineering Prototype (WSEP) installation at the Pacific Northwest Laboratory at the Hanford Plant, beginning early in 1966. The processes are the Oak Ridge National Laboratory pot-calcination process, the Hanford spray-calcination process, and the Brookhaven National Laboratory phosphate glass-fixation process.

1. Pot Calcination—This process involves evaporation of wastes to dryness followed by calcination of the residues at temperatures of 700 to 900°C. Calcination is the process of making dry, granular solids by heating. The temperature used is not high enough to melt the material. The last step is done in a pot, which then becomes the final storage container. When filled with calcined solids, the pot is sealed and shipped to permanent storage. This process offers versatility in processing several types of waste, produces a minimum amount of gases, and eliminates the need for packaging the product.

2. Spray Calcination—Over the past four years, personnel of the Pacific Northwest Laboratory have been investigating the merits of converting liquid wastes to solids by spray calcination in a heated tower. Liquid wastes are forced through a nozzle into the top of a tower, the sides of which are heated to about 800°C. As the droplets fall, they are first subjected to evaporation, then drying, and finally calcination. The resulting powder falls into a

heated pot. There the calcination is completed and forms a powdery or molten residue, depending on the waste material. In an experimental program numerous successful tests with high-level waste have been completed. This system handles many kinds of wastes, reduces vaporization and loss of certain fission products, and eliminates foaming and heat-transfer problems.

3. Phosphate-glass Fixation — For the past several years, Brookhaven National Laboratory personnel have been working on a continuous process for incorporating waste fission products into phosphate glass. This process offers the possibility of a continuous process in an all-liquid system and would allow easy heat control, removal of decomposition gases, mixing of ingredients, and general handling. The main parts of the plant are a feed-mixing tank, an evaporator, a high-temperature furnace with a platinum-lined crucible, and a gas processing system. The glass melt from the crucible is discharged into burial containers.

Three solidification processes have been undergoing pilot-plant demonstration at full radioactivity level at Pacific Northwest Laboratory since November 1966. The demonstration program is scheduled to be completed in 1970 with a series of engineering reports being made available to industry as separate phases of the program are completed.

HIGH-LEVEL WASTE STORAGE in natural geologic formations is being investigated. The production of stable solids that are insoluble and noncorrosive reduces the volume of waste to be stored and increases the safety of the storage activities. But what is the best way to store these solidified wastes? Remember that hundreds of years will be required for the natural decay of these wastes to harmless levels. Simple burial or disposal in the sea is not a suitable answer. Fortunately there are a number of natural geologic formations that might be suitable for permanent storage — they are well removed from man and free of groundwater that might otherwise leach and carry off some of the radioactive material to areas of possible human access.

1. Salt Deposits — At present salt appears to be the best disposal medium. Salt formations are usually dry, are impervious to water, and are not associated with usable

groundwater sources. The ability of salt to change shape under pressure causes rapid closure of fractures. Salt is sufficiently strong that large cavities formed by mining will not collapse. Salt deposits underlie some 400,000 square miles of the United States. And the estimated volume of high-level waste solids to be produced in the year 2000 would occupy less than 1% of the volume of salt now being mined each year.

An Oak Ridge National Laboratory program includes studies of possible effects of radiation on salt—on its physical properties, the possible production of chlorine, and the effects on movement under pressure and plastic flow when heated. This information is necessary before actual disposal facilities are designed.

A 19-month demonstration disposal of high-level radioactive waste solids was carried out in a salt mine at Lyons, Kansas. Spent reactor fuel was used in lieu of actual solidified wastes. During the field demonstration, the feasibility and safety of handling highly radioactive materials in an underground environment were demonstrated; the stability of salt under the effects of heat and radiation was shown; and data were obtained on the creep and plastic flow characteristics of salt for use in the design of an industrial salt disposal facility. Further engineering studies are now being carried out to determine the location and possible establishment of such a facility.

2. Bedrock Storage—In some cases it may not be necessary to reduce high-level wastes to solid form. At the AEC's Savannah River Plant, a study is under way for disposal of aged wastes in underground tunnels cut into bedrock. Underlying the plant at approximately 1000 feet is dense, crystallized bedrock. Exploratory drilling has provided information on the hydrology and geology of this formation and has verified the compatibility of the rock with the wastes to be stored. A layer of clay overlays the bedrock and separates it from the top layer of loose water-bearing sediment.

Three principal mechanisms delay the migration of wastes from the bedrock tunnels: the low rate of natural water movement, the impermeability and ion-exchange properties of the clay, and the ion-exchange properties of

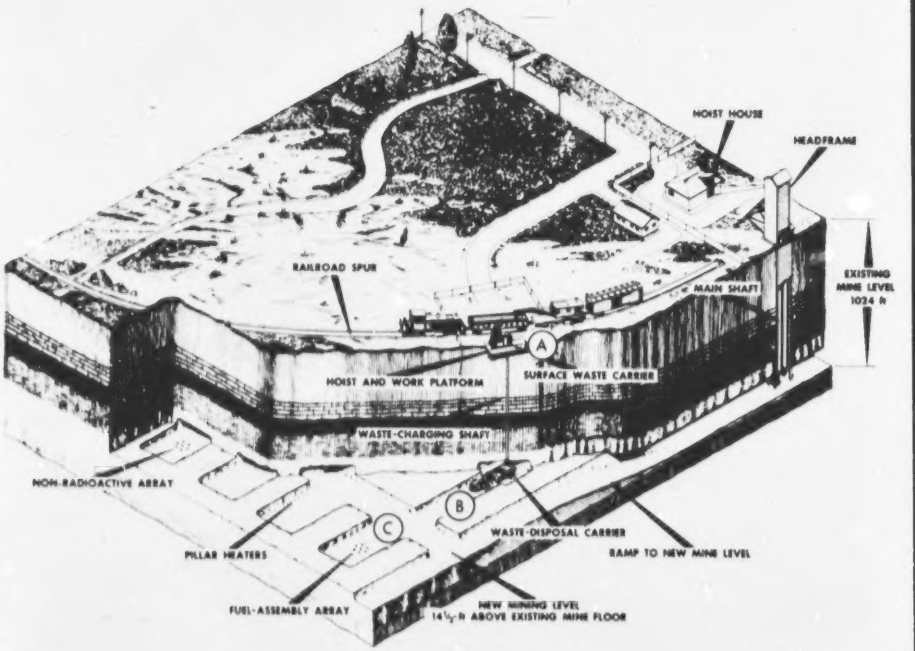

Figure 16 *The Carey Salt Company Mine in Lyons, Kansas, is the scene of a radioactive waste disposal experiment conducted by the Oak Ridge National Laboratory.*

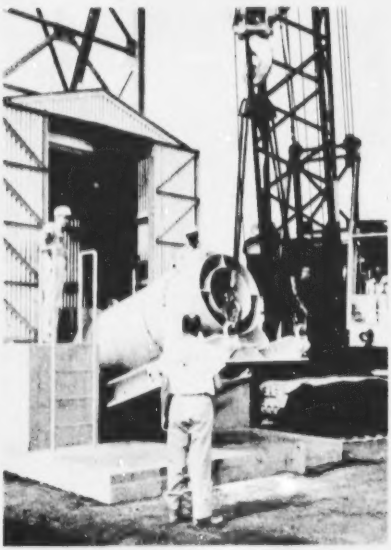

Photo A. A 30-ton lead cask is maneuvered into position over the 1000-foot waste charging shaft. This provides shielding for personnel.

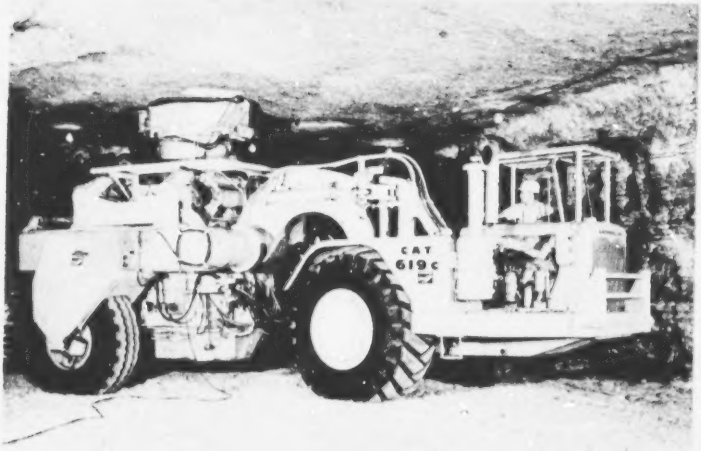

Photo B. Cannisters containing radioactive material are lowered down the shaft to a specially designed trailer coupled to a conventional two-wheel tractor, which carries them to the experimental area shown in photo C. This machinery was assembled inside the mine.

Photo C. Holes, 12 feet deep and lined with stainless steel, in the salt mine floor are used to contain radioactive fuel assemblies. The room is 30 feet wide, 60 feet long, and 14 feet high.

the top layers of earth. Each of these barriers is considered to be an adequate shield in itself. Since they would be encountered in succession, there is an ample factor of safety. Studies are now under way on how to remove and transfer wastes from the present storage tanks.

Low-level Waste Processing

When the nuclear industry was small, low-level wastes could be discharged to the environment without raising background radiation significantly. This will be less possible in the future because of the growth of the industry. It is important to develop more efficient methods for treating these large-volume wastes.

Although normal chemical processing of low-level wastes can remove approximately 90% of the contained radioactivity in a single treatment, multistage treatment is complex and costly. For this reason work is under way to develop more efficient and economical methods.

A specific goal is to decontaminate low-level wastes to an extent that would even permit direct consumption of the liquids by humans. Two treatment methods are being developed. Both involve scavenging-precipitation, but one is followed by an ion-exchange process and the other by a foam-separation process.

THE SCAVENGING-PRECIPITATION ION-EXCHANGE PROCESS has demonstrated that it can produce wastes of significantly lower residual activity than the lime-soda treatment now used. The low-level feed is adjusted to an alkaline condition in a mixing vessel, and a coagulant is added. The solution then flows to a slightly agitated tank (called a flocculator) in which insoluble materials agglomerate into large particles containing most of the fission products. The mixture then flows to another vessel (called a clarifier) and passes up through a layer of sludge that is continuously removed and packed for disposal. The clarified water then passes through a filter and is pumped through ion-exchange columns for removal of the remaining fission products, principally cesium-137 and strontium-90. Over a five-month period, the process treated 600,000 gallons of low-level waste, removing 99.99% of the strontium and 99.7% of the cesium.

THE FOAM-SEPARATION PROCESS for final decontamination of the filtered solutions from the scavenging-precipitation process just described is also under study. In this method foam is produced by adding detergent to the waste solution and bubbling air through it. The foam rises to the top of a column. Most of the radioisotopes cling to the surface of the bubbles and rise with the foam. The foam is drawn off the top and collapsed; it yields a small amount of liquid. The bulk of the waste solution, having been cleaned by the foam passing through it, is drawn from near the bottom of the column. So far, however, this appears to be less simple and less efficient than the use of ion-exchange resins.

Intermediate-level Waste Processing

A number of treating processes can be used for both low-level and intermediate-level liquid wastes. One of the most interesting studies, however, is one dealing with direct disposal of intermediate-level waste into shale or other suitable geologic formations. The technique is called hydraulic fracturing and has been borrowed from the oil industry. It has been under study for the past three years (see Figure 17).

The method requires the drilling of a well, followed by lateral cuts through the well casing into the rock formation, which are accomplished by jets of a sand–water mixture

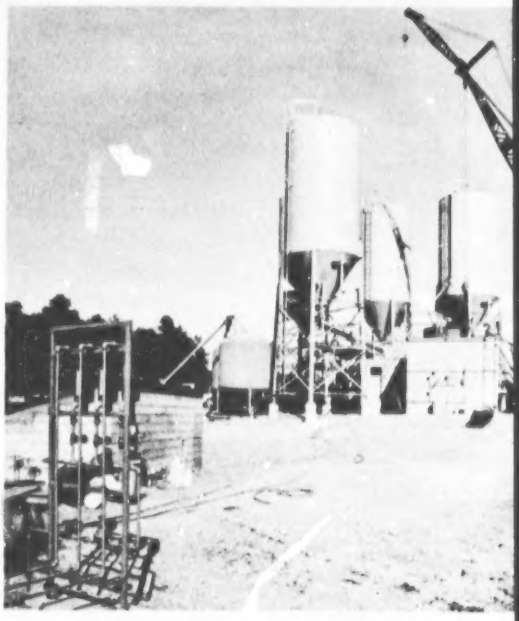

Figure 17 *Facilities for disposal of intermediate-level liquid wastes by injection into shale formations 1000 feet below ground level.*

or by shaped charges of explosive. A mixture of water, waste, and cement is pumped into the formation at high pressure; this cracks the rock and allows the mixture to move out in horizontal sheets that solidify in place.

Oak Ridge National Laboratory workers made test injections of material containing radioactive tracers in 1960. Later, core drilling provided information on the extent and thickness of the solidified material. Results were favorable, and early in 1964 a hydrofracturing plant was completed for injection of actual wastes. Approximately 250,000 gallons of intermediate level waste concentrate is now being disposed of routinely each year using this technique.

Environmental Studies

An important part of waste-management research is the study of environments surrounding atomic energy installations. Objectives are to determine the fate of radioactive materials released to waterways, to determine the mechanisms of their dispersion, to evaluate the hazards associated with disposal practices, to evaluate the usefulness of waterways for disposal, and to recommend appropriate long-term environmental-monitoring procedures.

The principal studies in the United States have been made of the Clinch–Tennessee River system below Oak Ridge, Tennessee; the Columbia River below Richland, Washington; and the Savannah River below Aiken, South Carolina. Similar studies have been made of the Ottawa River in Canada, the Thames River in England, and the Rhone River in France. For example, the comprehensive investigation on the Clinch and Tennessee Rivers is a multiagency effort to evaluate physical, chemical, and biological effects caused by the disposal of low-level radioactivity (see Figure 18). Water-sampling stations have been established at seven sites, located as far as 125 miles below Oak Ridge.

Studies have included dispersion tests with dyes and radioactive tracers, determination of the distribution of radioactivity in bottom sediments, methods of incorporation of radioactivity into the bottom sediments, and detailed analyses of the biological distribution of released radio-

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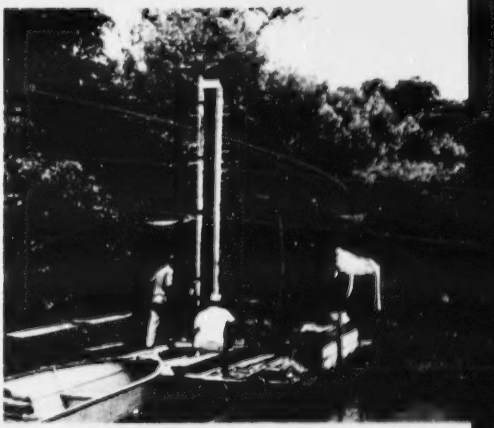

Figure 18 *Taking core samples of bottom sediments in the Clinch River in Tennessee.*

isotopes and the resulting dosages to human and animal life in the area.

Studies such as these are essential to our understanding of the effects of released radioactive wastes. This understanding must be thorough because no significant mechanism for the dispersal of radioactive materials and possible subsequent exposure of the public can be overlooked. Mankind needs the tremendous energy represented by nuclear fuels, but their use will create vast quantities of radioactive wastes. Disposal of these must never be allowed to harm man, his environment, or his natural resources. Radioactive waste management is dedicated to this objective.

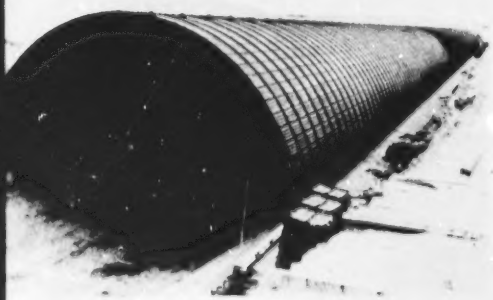

Figure 19 *Equipment disposal tunnel at the Hanford Plant in Richland, Washington. Radioactive chemical processing equipment, too large to be buried conveniently, is loaded onto flatcars and pushed into the 1700-foot tunnel. The tunnel will then be covered with earth.*

APPENDIX I

Naturally Occurring Radioisotopes Encountered in Mining, Milling, and Fuel Preparation in Uranium Fuel Cycle

Radioisotope	Atomic number	Percent found in natural uranium	Half-life	Radiation emitted*
		Uranium-238 Decay Chain		
Uranium-238	92	99.28	4.5×10^9 yr	α, γ
Thorium-234	90	1×10^{-9}	24.1 days	β, γ
Protactinium-234	91	5×10^{-14}	1.14 min	β, γ
Uranium-234	92	6×10^{-3}	2.5×10^5 yr	α, γ
Thorium-230	90	2×10^{-3}	8×10^4 yr	α, γ
Radium-226	88	4×10^{-6}	1622 yr	α, γ
Radon-222	86	2×10^{-10}	3.8 days	α
Polonium-218	84	1×10^{-13}	3.1 min	α
Lead-214	82	1×10^{-12}	26.8 min	β, γ
Bismuth-214	83	8×10^{-13}	19.7 min	β, γ
Polonium-214	84	1×10^{-15}	$\sim 10^{-4}$ sec	α
Lead-210	82	5×10^{-7}	22 yr	β, γ
Bismuth-210	83	3×10^{-10}	5 days	β
Polonium-210	84	8×10^{-9}	138 days	α, γ
Lead-206	82		Stable	
		Uranium-235 Decay Chain		
Uranium-235	92	0.71	7.1×10^8 yr	α, γ
Thorium-231	90	3×10^{-12}	25.6 hr	β, γ
Protactinium-231	91	3×10^{-5}	3.4×10^4 yr	α, γ
Actinium-227	89	2×10^{-8}	27 yr	α, β, γ
Thorium-227	90	5×10^{-11}	18.6 days	α, γ
Radium-223	88	3×10^{-11}	11.2 days	α, γ
Radon-219	86	1×10^{-16}	3.9 sec	α, γ
Polonium-215	84	6×10^{-20}	$\sim 10^{-3}$ sec	α
Lead-211	82	7×10^{-14}	36.1 min	β, γ
Bismuth-211	83	4×10^{-15}	2.1 min	α, γ
Thallium-207	81	9×10^{-15}	4.8 min	β, γ
Lead-207	82		Stable	

*α: alpha particle, a helium nucleus. γ: gamma ray, similar to X rays. β: beta particle, an electron.

APPENDIX II

Principal Fission-product Radioisotopes in Radioactive Wastes

Radioisotope	Atomic number	Half-life	Radiation emitted*
Krypton-85	36	4.4 hr (IT)† → 9.4 yr	$\beta, \gamma, e^- \rightarrow \beta, \gamma$
Strontium-89	38	54 days	β
Strontium-90	38	25 yr	β
Zirconium-95	40	65 days	β, γ
Niobium-95	41	90 hr (IT) → 35 days	$e^- \rightarrow \beta, \gamma$
Technetium-99	43	5.9 hr (IT) → 5×10^5 yr	$e^-, \gamma \rightarrow \beta$
Ruthenium-103	44	39.8 days	β, γ
Rhodium-103	45	57 min	e^-
Ruthenium-106	44	1 yr	β
Rhodium-106	45	30 sec	β, γ
Tellurium-129	52	34 days (IT) → 72 min	$e^-, \beta \rightarrow \beta, \gamma$
Iodine-129	53	1.7×10^7 yr	β, γ
Iodine-131	53	8 days	β, γ
Xenon-133	54	2.3 days (IT) → 5.3 days	$e^-, \beta \rightarrow \beta, \gamma$
Cesium-137	55	33 yr	β, γ
Barium-140	56	12.8 days	β, γ
Lanthanum-140	57	40 hr	β, γ
Cerium-141	58	32.5 days	β, γ
Cerium-144	58	590 days	β, γ
Praseodymium-143	59	13.8 days	β, γ
Praseodymium-144	59	17 min	β
Promethium-147	61	2.26 yr	β

*β: beta particle, an electron. γ: gamma ray, similar to X rays. e^-: internal electron conversion.

†IT: isomeric transition, internal.

APPENDIX III

Principal Activation-product Radioisotopes Produced by Neutron Irradiation of Nonfuel Materials

Radioisotope	Atomic number	Source and reaction*	Half-life	Radiation emitted†
		Air and Water		
Tritium (H-3)	1	^{2}H (n,γ)	12.3 yr	β, γ
Carbon-14	6	^{14}N (n,p)	5700 yr	β
Nitrogen-16	7	^{16}O (n,p)	7.3 sec	β, γ
Nitrogen-17	7	^{17}O (n,p)	4.1 sec	β
Oxygen-19	8	^{18}O (n,γ)	30 sec	β, γ
Argon-41	18	^{40}A (n,γ)	1.8 hr	β, γ
		Sodium		
Sodium-24	11	^{23}Na (n,γ)	15 hr	β, γ
Sodium-22	11	^{23}Na (n,2n)	2.6 yr	β^+, γ
Rubidium-86	37	^{85}Rb (n,γ) (impurity in sodium coolant)	19.5 hr (IT)‡ → 1 min	β, γ → K, γ
		Alloys		
Aluminum-28	13	^{27}Al (n,γ)	2.3 min	β, γ
Chromium-51	24	^{50}Cr (n,γ)	27 days	β^+, K, γ
Manganese-56	25	^{56}Fe (n,p)	2.6 hr	β, γ
Iron-55	26	^{54}Fe (n,γ)	2.9 yr	K
Iron-59	26	^{59}Co (n,p)	45 days	β, γ
Copper-64	29	^{63}Cu (n,γ)	12.8 hr	β, γ, β^+, K
Zinc-65	30	^{64}Zn (n,γ)	250 days	β^+, e^-, γ
Tantalum-182	73	^{181}Ta (n,γ)	115 days	β, γ
Tungsten-187	74	^{186}W (n,γ)	24 hr	β, γ
Cobalt-58	27	^{58}Ni (n,p)	71 days	β^+, γ
Cobalt-60	27	^{59}Co (n,γ) (also purposeful irradiation)	5.3 yr	β, γ
Phosphorus-32	15	^{31}P (n,γ) (purposeful irradiation)	14.3 days	β

*(n,γ): absorbs neutron, emits gamma. (n,p): absorbs neutron, emits proton.

†β: beta particle, an electron. γ: gamma ray, similar to X rays. β^+: positively charged electron. K: orbital electron capture into nucleus. e^-: internal electron conversion.

‡IT: isomeric transition, internal.

APPENDIX IV
List of Firms Licensed to Receive and Dispose of Radioactive Wastes

1. Firms Licensed by U. S. Atomic Energy Commission

Allied-Crossroads Nuclear Corp.
201 Victory Road
Dorchester, Massachusetts 02122

New England Tank Cleaning Co.
135 First Street
Cambridge, Massachusetts 02138

The Walker Trucking Company
1283 East Street
New Britain, Connecticut 06050

*2. Firms Licensed by AEC and Agreement States**

California Salvage Company
700-745 North Pacific Avenue
San Pedro, California 90731

Nuclear Engineering Company, Inc
Box 594
Walnut Creek, California 93002

California Nuclear, Inc.
2323 South Ninth Street
Lafayette, Indiana (HQ) 47905

Nuclear Engineering Company, Inc.
Box 146
Burns Building
Morehead, Kentucky 40351

Laboratory for Electronics, Inc.
Tracerlab Division
1601 Trapelo Road
Waltham, Massachusetts 02154

Laboratory for Electronics, Inc.
Tracerlab Division
2030 Wright Avenue
Richmon, California 94804

Long Island Nuclear Services Corp.
Station Road
Bellport, New York 11713

Radiological Service Co., Inc.
35 Urban Avenue
Westbury, New York 11590

3. Firms Licensed Entirely by Agreement States†

Consolidated American Services, Inc.
12600 South Daphne Avenue
Hawthorne, California 90250

Nuclear Fuel Services, Inc.
Box 124
West Valley, New York 14171

U. S. Nuclear Corporation
801 North Lake Street
Burbank, California 91502

William Wayne Electronics
Hastings Radiochemical Works
Box 60448
Houston, Texas 77060

*States which have sufficient interest and which develop adequate controls and regulations may, by agreement with the AEC Division of Licensing and Regulation, assume control of waste-handling activities within their boundaries. Licensing by the AEC is required for interstate activities.

†This list may not be complete. Current information can be obtained from the Department of Health of the particular state involved. The following states have entered into agreements for control by state regulation: Arkansas, California, Florida, Kansas, Kentucky, Mississippi, New York, North Carolina, Texas, Oregon, and Tennessee.

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The following reports are available from the Clearinghouse for Federal Scientific and Technical Information, 5285 Port Royal Road, Springfield, Virginia 22151.

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Low Level Radioactive Wastes: Their Treatment, Handling, and Disposal, Conrad P. Straub, produced by the AEC's Division of Technical Information and available from the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402, 1964, 430 pp., $1.50.

Motion Pictures

Available for loan without charge from the AEC Headquarters Film Library, Division of Public Information, U. S. Atomic Energy Commission, Washington, D. C. 20545, and from other AEC film libraries.

Living with Radiation, 28 minutes, sound, color, 1958. Produced for the AEC's Idaho Operations Office by Lookout Mountain Air Force Station. This film documents the AEC radiation safety program by using procedures at the National Reactor Testing Station in Idaho as illustrative examples. It includes waste storage and disposal, personnel-protection methods, and other relevant topics.

Isotopes, 20 minutes, sound, color, 1959. Produced by the AEC's Oak Ridge National Laboratory. This film explains radioactivity and methods for producing radioisotopes, including separation of isotopes from high-level wastes.

Regulation of Atomic Radiation, 28½ minutes, sound, color, 1963. Produced by the AEC. This film surveys AEC work in the licensing and regulation of the uses of nuclear materials. It shows the control of radioactive materials from the time they leave the mine until they become waste.

Reactor Fuel Processing, 20 minutes, sound, color, 1958. Produced by the AEC's Oak Ridge National Laboratory. This film covers the chemical processing of irradiated reactor fuels and waste-disposal operations.

Atoms on the Move: Transportation of Radioactive Materials, 24 minutes, color, 1966. Produced by Bennie Korzen Productions for the AEC. Ores, reactor fuel, weapons, radioisotopes for medicine, industry, research, and atomic wastes are shown in transit. Safety aspects, including accident research, and responsibilities of federal agencies are discussed.

Working with Radiation, 29 minutes, black and white, 1962. Produced by the AEC's Argonne National Laboratory. Precautions and various methods for handling radioactive materials including wastes are illustrated.

PHOTO CREDITS

Cover courtesy Oak Ridge National Laboratory (ORNL)
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Figure 4 ORNL
Figure 6 Union Carbide Corporation
Figure 7 ORNL
Figure 8 Savannah River Plant
Figure 9 Brookhaven National Laboratory
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Figure 13 E. I. Du Pont de Nemours & Company
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Figure 17 ORNL
Figure 18 ORNL
Figure 19 Hanford Plant

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